Biol Invasions
https://doi.org/10.1007/s10530-022-02824-4

ORIGINAL PAPER

Prioritization of invasive alien species with the potential to threaten agriculture and biodiversity in Kenya through horizon scanning

Joseph Mulema · Roger Day · Winnie Nunda · Komivi Senyo Akutse · Anani Y. Bruce · Sospeter Gachamba · Solveig Haukeland · Ruth Kahuthia-Gathu · Staline Kibet · Asenath Koech · Thomas Kosiom · Douglas Watuku Miano · George Momanyi · Lucy Kananu Murungi · James Wanjohi Muthomi · Julianna Mwangi · Maina Mwangi · Nicholas Mwendo · John Huria Nderitu · Johnson Nyasani · Miriam Otipa · Sarah Wambugu · Eric Were · Fernadis Makale · Laura Doughty · Steve Edgington · Ivan Rwomushana · Marc Kenis

Received: 7 September 2021 / Accepted: 6 May 2022

Abstract Invasive alien species (IAS) rank among the most significant drivers of species extinction and ecosystem degradation resulting in significant impacts on socio-economic development. The recent exponential spread of IAS in most of Africa is attributed to poor border biosecurity due to porous borders that have failed to prevent initial introductions. In addition, countries lack adequate information about potential invasions and have limited capacity to reduce the risk of invasions. Horizon scanning is an approach that prioritises the risks of potential IAS through rapid assessments. A group of 28 subject matter experts used an adapted methodology to assess 1700 potential IAS on a 5-point scale for the likelihood of entry and establishment, potential socio-economic impact, and impact on biodiversity. The individual scores were combined to rank the species

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10530-022-02824-4.

J. Mulema (✉) · R. Day · W. Nunda · F. Makale · I. Rwomushana
CABI, Nairobi, Kenya
e-mail: j.mulema@cabi.org

K. S. Akutse · S. Haukeland
International Centre of Insect Physiology and Ecology (ICIPE), Nairobi, Kenya

A. Y. Bruce
International Maize and Wheat Improvement Center (CIMMYT), Nairobi, Kenya

S. Gachamba · A. Koech · T. Kosiom · G. Momanyi · J. Mwangi · E. Were
Kenya Plant Health Inspectorate Service, Nairobi, Kenya

R. Kahuthia-Gathu · M. Mwangi
Kenyatta University, Nairobi, Kenya

S. Kibet · D. W. Miano · J. W. Muthomi · J. H. Nderitu
University of Nairobi, Nairobi, Kenya

L. K. Murungi
Jomo Kenyatta University of Science and Technology, Nairobi, Kenya

N. Mwendo · S. Wambugu
Pest Control Products Board (PCPB), Nairobi, Kenya

J. Nyasani · M. Otipa
Kenya Agricultural and Livestock Research Organization, Nairobi, Kenya

L. Doughty
CABI, Wallingford, UK

S. Edgington
CABI, Egham, UK

M. Kenis
CABI, Delémont, Switzerland

Published online: 31 May 2022

according to their overall potential risk for the country. Confidence in individual and overall scores was recorded on a 3-point scale. This resulted in a priority list of 120 potential IAS (70 arthropods, 9 nematodes, 15 bacteria, 19 fungi/chromist, 1 viroid, and 6 viruses). Options for risk mitigation such as full pest risk analysis and detection surveys were suggested for prioritised species while species for which no immediate action was suggested, were added to the plant health risk register and a recommendation was made to regularly monitor the change in risk. By prioritising risks, horizon scanning guides resource allocation to interventions that are most likely to reduce risk and is very useful to National Plant Protection Organisations and other relevant stakeholders.

Keywords Invasive alien species · Horizon scanning · Pest risk · Risk prioritization · Risk management

Introduction

Invasive alien plant pests cause increasingly significant impacts on the economy and livelihoods in Sub-Saharan Africa (SSA) (Eschen et al. 2021). In the last decade, Kenya has been particularly affected by new introductions of invasive plant pests[1] which damage cultivated plants. For example, in 2011, a new disease of maize was reported in the Bomet and Naivasha districts of Kenya (Andae 2012; Makiche 2012). The disease was later identified as maize lethal necrosis disease (MLND) (Wangai et al. 2012). It is caused mainly by co-infection with maize chlorotic mottle virus (MCMoV), a virus first reported in South America (Xie et al. 2011; Braidwood et al. 2018), and other cereal viruses (Louie 1980; Adams et al. 2013; Stewart et al. 2017). Following the first report in Kenya, MLND spread to other countries in Eastern Africa (Lukanda et al. 2014; Adams et al. 2014; Kagoda et al. 2016; Mengesha et al. 2019; Kiruwa et al. 2020).

Since then, Kenya has reported other destructive invasive plant pests such as tomato leaf miner, *Pthorimaea* (=*Tuta*) *absoluta* in 2013 (Guimapi et al. 2016); potato cyst nematodes (PCN), *Globodera rosotchiensis* in 2015 (Mwangi et al. 2015) and *G. pallida* in 2016 (Mburu et al. 2020); papaya mealybug, *Paracoccus marginatus* in 2016 (Macharia et al. 2017); fall armyworm, *Spodoptera frugiperda* in 2017 (De Groote et al. 2020); and the spotted-wing drosophila, *Drosophila suzukii* in 2019 (Kwadha et al. 2021). All these, and other invasive plant pests have caused enormous strain on a sector that supports millions of livelihoods in Kenya. For instance, De Groote et al. (2020) demonstrated that *S. frugiperda* caused losses of about a third of the annual maize production in Kenya. A survey in 2018 in Kenya showed 41% of tomato farmers had lost a large proportion of their crop to *P. absoluta*, with a mean seasonal production loss of 114,000 tonnes of tomatoes, based on farmers' own estimates (Rwomushana et al. 2019). At continental scale, Eschen et al. (2021) recently estimated the annual cost of invasive alien species (IAS) to African agriculture. The two most "costly" invasive plant pests were *P. absoluta* and *S. frugiperda*, accounting for USD 11.4 Bn and USD 9.4 Bn per annum, respectively. Invasive plant pests have also been demonstrated to affect biodiversity. For instance, in Kenya, increased density of *Parthenium hysterophorus* correlated with a reduction in species diversity and richness (Murono et al. 2018) while Maundu et al. (2009) demonstrated immense impacts on semi-arid and arid ecosystems caused by *Prosopis juliflora*.

Invasive alien species may be introduced to countries through various pathways.[2] Intentional or unintentional human-mediated activities are frequently involved, but natural spread also occurs from native or areas where they have been introduced, aided majorly by weather (Desneux et al. 2011; Nagoshi et al. 2018; Essl et al. 2019). International trade remains a major cause of spread of invasive pests (Westphal et al. 2008). Unfortunately,

[1] The term "**pest**" is used within the context of the International Plant Protection Convention (IPPC) and refers to any species, strain, or biotype of plant, animal, or pathogenic agent injurious to plants or plant products (International Standards for Phytosanitary Measures Number 5). Pathogenic agents include bacteria, fungi, oomycetes, phytoplasma, viroid and virus while animals may include arthropods, molluscs, and nematodes (IPPC Secretariat 2021).

[2] The term "**pathway**" is used within the context of the IPPC and refers to any means that allows entry and spread of a pest (International Standards for Phytosanitary Measures Number 5) (IPPC Secretariat 2021).

once biological invasions are recorded anywhere in Africa, the organisms can spread across the continent unabated as was observed with *P. absoluta*, *S. frugiperda* and MLND (Mahuku et al. 2015; Guimapi et al. 2016). While it is unrealistic to expect border security to stop the spread of invasive pests within SSA, the situation could be improved by availability of timely and adequate information at the national and regional levels on the highest risk species and enhanced ability to share this information to support planning and implementation of sustainable management strategies such as prevention of invasions through the early detection, containment and eventual eradication of invasive species (Roy et al. 2014, 2017; Essl et al. 2015; Faulkner et al. 2017, 2020). This information can also be utilised to constrict pathways by reducing and limiting the means of entry and spread, intercepting movements at border points, and assessing risk of planned imports (Simberloff et al. 2013).

Horizon scanning of (IAS) is an approach that can be used to generate information on possible biological invasions, and so support planning and management at country and regional level, as well as inform policy and practice (Caffrey et al. 2014). It is the systematic search for potential biological invasions and an assessment of their potential socio-economic impacts and potential impacts on biodiversity, considering possible opportunities for mitigating the impacts (Sutherland et al. 2008, 2010a, b; Roy et al. 2014). The approach has been used at country level such as in Cyprus to determine non-native species that could become invasive (Peyton et al. 2019), Great Britain (Roy et al. 2014), Spain (Gassó et al. 2009; Bayón and Vilà 2019) and at the regional level such as the European Union (Roy et al. 2019), Central Europe (Weber and Gut 2004), Western Europe (Gallardo et al. 2016), and the United Kingdom (Sutherland et al. 2008). Building on the above background, a study was conducted in 2018 to utilize horizon scanning to identify and assess alien species that are not currently recorded as present in Kenya but could be introduced and become invasive in future threatening the economy through impacting on agriculture and biodiversity. The assessment covered arthropod pests, nematode, and pathogenic organisms (bacteria, fungi, oomycetes, phytoplasma, viroid, and viruses).

Materials and methods

The prioritisation was carried out by a panel of 28 Subject Matter Experts (SMEs) convened from research and academic institutions in Kenya. The SMEs had experience in the following areas: entomology, bacteriology, mycology, nematology, and virology. The SMEs were allocated to three thematic groups based on their expertise: Entomology (18), Nematology (2) and Pathology which included bacteriology, mycology, and virology (8). An adapted version of the consensus method developed for ranking IAS (Sutherland et al. 2011; Roy et al. 2014, 2019) was used to derive a ranked list of invertebrates (arthropods and nematodes) and pathogenic organisms (bacteria, fungi/chromista, viroid, and viruses) that are harmful to plants and could possibly enter Kenya in the future and become invasive. The approach involved the following steps:

Step 1. Preliminary horizon scanning

At the first meeting in June 2018, the SMEs made a preliminary selection of pests that had not yet been recorded as present in Kenya. This exercise was carried out using the premium version of the horizon scanning tool included in the CABI's Crop Protection Compendium (CPC) (CABI 2021a). In this tool, information from the CPC datasheets is used to generate a list of species that are absent from the selected 'area at risk' (Kenya) but present in specified source areas. Initially, the source areas were all countries within and outside Africa, which produced a list of over 1700 species. The SMEs reviewed the list by removing all organisms that were not arthropods, nematodes and pathogenic organisms (bacteria, fungi/chromista, viruses and viroid); species of arthropods, nematodes and pathogenic organisms known to already occur in Kenya (even though not reported as present, so appearing as absent in the CPC); and species of arthropods, nematodes and pathogenic organisms unanimously considered as not important pests for plants in Kenya, e.g., species that are specific to a plant genus that does not occur in the country.

A list of 194 species (108 arthropods, 9 nematodes, 15 bacteria, 48 fungi/chromista, 1 viroid, and 13 viruses) was obtained. This was further refined by selecting only arthropods, nematodes and pathogenic organisms for which a full datasheet[3] was available in the CPC and the Invasive Species Compendium (ISC) (CABI 2021b) leaving 100 species (62 arthropods, 9 nematodes, 7 bacteria, 16 fungi/chromista, 1 viroid, and 5 viruses). Species with a full datasheet in the CPC but not in the ISC were eliminated because without a full datasheet, there was not enough information to evaluate the species for characteristics of invasiveness; however, it also could indicate the species had not been invasive anywhere.

The SMEs from the National Plant Protection Organisation (NPPO), Kenya Plant Health Inspectorate Service (KEPHIS) added an additional 20 species not reported as present in Africa, but which were adjudged as potentially being of phytosanitary concern because they affect value chains key to the Kenyan economy. For instance, fruit flies such as *Anastrepha ludens*, *A. obliqua*, *Bactrocera tryoni*, and *D. suzuki* were included because of their effect on the fruit industry; the bacterial ring rot causal agent, *Clavibacter sepedonicus* and blackleg and soft rot pathogens, *Dickeya dadantii*, *D. dianthicola*, *D. solani*, *D. zea* and *Pectobacterium atrosepticum* because of their effect on the potato (*Solanum tuberosum*) value chain where zero tolerance in seed is emphasized. The 20 species included 8 arthropods, 8 bacteria, 3 fungi/chromista and 1 virus (indicated in Supplementary file S2). This resulted in a list of 120 species which included 70 arthropods, 9 nematodes, 15 bacteria, 19 fungi/chromista, 1 viroid, and 6 viruses which were scored as described below.

Step 2. Description of the scoring system

The risk scoring system used was based on that described by Roy et al. (2019) but was modified during the first meeting so that there was an agreed and common understanding of the terminology used, applicable to the Kenyan context. Roy et al. (2019) assessed the likelihood of arrival, establishment, spread, and magnitude of potential negative impact on biodiversity and ecosystem services while in this assessment, the likelihood of entry (arrival), establishment, and potential magnitude of socio-economic impact and potential magnitude of impact on biodiversity were assessed. The likelihood of spread was not considered because once an alien species arrives ashore, exponential spread within and between countries in SSA has been observed assisted majorly by human-mediated activities especially if the criteria for entry and establishment are met and the key pathways are available (Mahuku et al. 2015; Kansiime et al. 2017; De Groote et al. 2020). A 5-score system for the four parameters (entry, establishment; socio-economic and biodiversity impact) where 1 suggested unlikely to enter or establish; or minimal impact and 5 suggested very likely to enter or establish; major impact was used. A detailed scoring system version is provided in Supplementary file S1 but briefly outlined below.

To assesses likelihood of entry, 1 suggested absent from Africa and unlikely to be in the imported commodity; 2, absent from Africa but likely to be infrequently imported on a commodity; 3, present in Africa (not in neighbouring countries) and spreads slowly; or absent from Africa but: recently spreads very fast on several continents, or often associated to a commodity commonly imported, or frequently intercepted in Kenya; 4, present in Africa (not in neighbouring countries) and spreads fast, or in a neighbouring country and spreads slowly; and 5, present in a neighbouring country (Ethiopia, Somalia, South Sudan, Tanzania, and Uganda) and spreads fast. To assess the likely pathways of arrival, three likely pathways as defined by Hulme et al., (2008) were considered, unaided (UN) which comprised mainly natural dispersal; commodity (CO) which comprised intentional introduction as a commodity or with a commodity or unintentional introduction with a commodity (contaminant); and stowaway/hitchhiker (ST) which comprised vectors. Pathogenic organisms especially viruses and viroid which could be carried by vectors spreading through natural dispersal (UN), the stowaway pathway was considered although the commodity (CO) pathway was also considered if they were seed-borne, hence could come with the commodity as contaminants. The stowaway pathway was also considered for soil-borne pathogenic organisms which could unintentionally be introduced with soil.

[3] Full datasheets comprise fully referenced sections on taxonomy and nomenclature; distribution, habitat, identification, biology, and ecology; species associations; pathways for introduction, impacts, and management, complemented by images and maps, and supported by abstracts and full-text articles (CABI 2021a, b).

To assess likelihood of establishment, (1) suggested Kenya is climatically unsuitable or host plants are not present; (2) only few areas in Kenya climatically suitable; or host plants rare; (3) large areas in Kenya climatically suitable and host plants rare; or only few areas in Kenya climatically suitable but host plants at least moderately abundant; (4) large areas in Kenya climatically suitable and host plants moderately abundant; and (5) large areas in Kenya climatically suitable and host plants very abundant. For the potential magnitude of socio-economic impact, (1) suggested the species does not attack plants that are cultivated or utilised; (2) the species damages plants that are only occasionally cultivated or utilised; (3) the species damages plants that are regularly cultivated or utilised but without threatening the cultivation, utilisation, or trade of this crop; (4) the species has the potential to threaten, at least locally, the cultivation of a plant that is regularly cultivated or utilised; or to regularly attack a crop that is key for the Kenyan economy without threatening the latter; and (5) the species has the potential to threaten, at least locally, a crop that is key for the Kenyan economy. For potential magnitude of impact on biodiversity, (1) suggested the species will not affect any native species; (2) the species will affect individuals of a native species without affecting its population level; (3) the species has the potential to lower the population levels of a native species; (4) the species has the potential to locally eradicate a native species or to affect populations of a protected or keystone species; and (5) the species has the potential to eradicate a native species or to locally eradicate a keystone species.

Step 3. Scoring of species

After a group training at the first workshop, the scoring of species was done independently by all SMEs as assigned to respective thematic groups. Except for entomology and nematology thematic groups, SMEs in the pathology group assessed species based on their expertise. For instance, bacteria were assessed by bacteriologists; fungi and oomycetes by mycologists; and viruses and viroid by virologists. However, some SMEs were knowledgeable in all disciplines. Scores below three were considered low risk because of the low effect on likelihood of entry, establishment, economic as well as biodiversity damage; scores of three were considered moderate while scores above 3 (4 and 5) presented a high risk because they had an opposite effect to the low scores. For each species, confidence was estimated for each score for, the likelihood of entry; establishment; potential magnitude of socio-economic impact; and potential impact on biodiversity; likely pathway of arrival; and for the overall score following Blackburn et al. (2014). The rating proposed by Blackburn et al. (2014) was originally modified from the EPPO pest risk assessment decision support scheme (OEPP/EPPO 2012). The information to support the scores and confidences and the likely pathways was obtained from compendia (CPC and ISC), published (journal articles and reviews), and grey literature (conference papers and proceedings; dissertations and theses; government documents and reports and newspaper articles). The SMEs also relied on their existing knowledge for assessing the species. The likely pathway of arrival and associated confidence levels were used to help focus discussions on the possibility of entry and establishment but did not contribute to the overall score. The assessments were compiled and returned to all assessors before the consensus workshop.

The overall score was obtained by the following formula:

$$\begin{aligned}&\text{Likelihood of entry} \times \text{likelihood of establishment}\\&\quad\times (\text{magnitude of socio - economic impact}\\&\qquad+ \text{magnitude of impact on biodiversity}).\end{aligned}$$

Step 4. Consensus workshop

In December 2018, a consensus workshop was held for all assessors (SMEs). The assessments for each thematic group were reviewed one by one, and any discrepancies between scores were discussed among the assessors. The assessors had the opportunity to modify their scores according to the opinions of the other SMEs, but reaching consensus was not imperative. The overall risk score for a species was calculated using the median score for the four parameters, rather than the mean. This overall score was validated by the assessors in each thematic group through consensus, and in cases of disagreement, the individual scores, and the evidence on which they were based were re-discussed. The assessors who could not attend the second workshop were able to comment on the scores by email. The overall score was used to rank species according to their potential threat for Kenya.

Step 5. Finalising the ranked list

After the workshop, discussions were carried out among the SMEs to suggest the next course of action for the highest ranked species. A high ranked species was any species with a minimum score of 54 (according to the formula used) and above, because such a species scored a three for all the assessable attributes or more than a three in at least three or more attributes. This score of three suggested the situation turned more towards the possibility of entry, establishment, and higher impact (social-economic or biodiversity). However, only the top 20 species were selected for follow-up action as not all could be addressed in case the NPPO (KEPHIS) decided to consider preventive action due to limited resources. For arthropods, 21 species were selected because the 20th and 21st species tied on score (90) while all nematodes were selected because they were few yet the least had a risk score of 54. The suggested actions included considering whether a full pest risk analysis was merited; whether any changes to or additional preventive measures might be required; possible establishment of surveillance and early warning activities; and development of contingency plans to allow a rapid and effective response if a particular species was detected. The type of action suggested for a particular species was based on the importance of the value chain and the status of the alien species in Africa and neighbouring countries. Species for which immediate action was not suggested (not in the top 20 prioritised species), a plant health risk register (Baker et al. 2014) was recommended to which they were added. This will allow regular monitoring through reassessment to determine possible change in their risk status. The presence/absence in Kenya was again checked for all species in June 2021 by searching published documents.

Results

The full results of the assessments are provided in the Supplementary file S2 while the 21 arthropods, 9 nematodes and 20 pathogenic species prioritised with follow-up actions are presented in Tables 1, 2 and 3 respectively. All assessments are presented as agreed in December 2018, but in the discussion, we note where risks are likely to have changed since then, for example due to recent spread making introduction more likely.

Arthropods

In total, 70 arthropod species were assessed which included 69 insects and 1 mite. Six of the species had not been recorded in Africa at the time of the assessment while 13 species were recorded in neighbouring countries (Ethiopia, Somalia, Sudan, Tanzania, and Uganda). The overall risk scores ranged from 6 to 160 with 11 of the 70 species that scored a minimum of 54 and above (high scorers) had already been reported in neighbouring countries (Supplementary file S2). Only one mite, *Brevipalpus lewisi,* had an overall score of 60. The prioritised species (21) for follow-up actions included eight Hemiptera, four Coleoptera, three Diptera, three Lepidoptera, two Hymenoptera, and one Thysanoptera. The top five species included two species of the whitefly *Bemisia tabaci* complex, MEAM1 and MED, the peach fruit fly *Bactrocera zonata*, the yellow crazy ant *Anoplolepis gracilipes*, and the Southern armyworm *Spodoptera eridania*. Most of the arthropods (89%) were adjudged likely to arrive as contaminants on commodities, i.e., on their host plants, 16% were likely to arrive as stowaways (also referred to as hitchhikers), while 6% are good fliers so likely to enter unaided (Supplementary file S2). Because some species could enter the country through multiple pathways, that's why the percentages do not add up to 100. Suggestions for the most needed actions for the 21 prioritised species included mostly full PRAs and surveys or surveillance for their presence or introduction in the country in particular, species that have been reported in neighbouring countries (Table 1). It is recommended that the rest of the species (not prioritised) are added to the plant health risk register to regularly assess change in risk.

Nematodes

Nine nematodes were assessed with least risk scores of 54 obtained for *Heterodera goettingiana* and a maximum score of 90 obtained for the groundnut testa nematode, *Aphelenchoides arachidis* (Table 2 and Supplementary file S2). All assessed species

Table 1 The 21 prioritised arthropod species and the suggested actions

Species	Order	Source	Present in neighbouring country?	Countries	Score	Suggested actions
Bemisia tabaci (Gennadius) (MEAM1)	Hemiptera	CPC and ISC	No		160	Sample *B. tabaci* in Kenya for molecular analyses to assess which sibling species is present in the country
Bactrocera zonata (Saunders)	Diptera	CPC and ISC	No		140	Conduct a full PRA and surveillance
Anoplolepis gracilipes (Smith)	Formicidae	CPC and ISC	Yes	Tanzania	140	Prevention and early detection programme against invasive ants
Bemisia tabaci (Gennadius) (MED)	Hemiptera	CPC and ISC	No		140	Sample *B. tabaci* in Kenya for molecular analyses to assess which sibling species is present in the country
Spodoptera eridania (Stol)	Lepidoptera	CPC and ISC	No		130	Conduct a full PRA; surveillance; international collaboration to define a continental strategy to monitor the spread and develop management options
Bruchus pisorum (L.)	Coleoptera	CPC and ISC	Yes	Ethiopia	120	Early detection, inspections
Phenacoccus solenopsis Tinsley	Hemiptera	CPC and ISC	No		120	Conduct surveys in the country to assess its presence (records in Europe of interceptions from Kenya); conduct a full PRA
Thrips palmi Karny	Thysanoptera	CPC and ISC	No		120	Early detection, inspections including using molecular identification tools
Euwallacea fornicatus (Eichhoff)	Coleoptera	CPC and ISC	No		112	Conduct a full PRA
Monomorium destructor (Jerdon)	Hymenoptera	CPC and ISC	Yes	Ethiopia and Somalia	112	Prevention and early detection programme against invasive ants
Rastrococcus invadens Williams	Hemiptera	CPC and ISC	No		112	Conduct surveillance
Rhynchophorus ferrugineus (Olivier)	Coleoptera	CPC and ISC	No		112	Conduct a full PRA including climate model
Cacoecimorpha pronubana (Hübner)	Lepidoptera	CPC and ISC	No		105	Conduct a full PRA
Ceratitis quinaria (Bezzi)	Diptera	CPC and ISC	Yes	Tanzania	100	Conduct a full PRA and general fruit flysurveillance

Table 1 (continued)

Species	Order	Source	Present in neighbouring country?	Countries	Score	Suggested actions
Glycaspis brimblecombei Moore	Hemiptera	CPC and ISC	Yes	Ethiopia, Tanzania and Uganda	100	Found in Kenya after horizon scanning. Conduct biological control
Pseudaulacaspis pentagona (Targioni Tozzetti)	Hemiptera	CPC and ISC	Yes	Tanzania	100	Conduct a full PRA and surveillance to assess its potential presence in
Trogoderma granarium Everts	Coleoptera	CPC and ISC	Yes	Somalia	100	Early detection, inspections
Agrius cingulata (F.)	Lepidoptera	CPC and ISC	No		96	Conduct a full PRA
Dialeurodes citri (Ashmead)	Hemiptera	CPC and ISC	No		96	Conduct a full PRA
Neoceratitis cyanescens (Bezzi)	Diptera	CPC and ISC	No		90	Conduct a full PRA and general fruit fly surveillance
Pseudococcus viburni Signoret	Hemiptera	CPC and ISC	No		90	Conduct a full PRA

Table 2 The nine nematode species and the suggested actions

Species	Kingdom	Source	Present in a neighbouring country?	Countries	Score	Suggested actions
Aphelenchoides arachidis Bos	Aphelenchoididae	CPC and ISC	Y	Uganda	90.0	Conduct a full PRA and surveillance
Ditylenchus africanus Wendt, Swart, Vrain & Webster	Anguinidae	CPC and ISC	N		84.0	Conduct a full PRA and surveillance
Ditylenchus destructor Thorne	Anguinidae	CPC and ISC	N		84.0	Conduct a full PRA and surveillance
Heterodera cajani Koshi	Heteroderidae	CPC and ISC	N		73.5	Conduct a full PRA and surveillance
Heterodera glycines (Ichinohe)	Heteroderidae	CPC and ISC	N		73.5	Conduct a full PRA and surveillance
Globodera tabacum Lownsbery and Lownsbery	Heteroderidae	CPC and ISC	N		72.0	Conduct a full PRA and surveillance
Meloidogyne graminicola Golden & Birchfield	Meloidogynidae	CPC and ISC	N		72.0	Conduct a full PRA and surveillance
Aphelenchoides ritzemabosi Schwartz	Aphelenchoididae	CPC and ISC	N		66.0	Conduct a full PRA and surveillance
Heterodera goettingiana Liebscher	Heteroderidae	CPC and ISC	N		54.0	Conduct a full PRA and surveillance

Table 3 The 20 prioritised pathogenic species and the suggested actions

Species	Kingdom	Source	Present in neighbouring country?	Countries	Score	Suggested actions
Xanthomonas citri (Hasse) Constantin, Cleenwerck, Maes, Baeyen, Van Malderghem, De Vos, Cottyn	Bacteria	CPC and ISC	Yes	Ethiopia, Somalia, and Tanzania	175	Survey for its potential presence in Kenya
Ceratocystis fimbriata (Ellis & Halsted)	Fungus	CPC and ISC	Yes	Uganda	175	Survey for its potential presence in Kenya
Dickeya zeae (Samson, Legendre, Christen, Fischer-Le Saux, Achouak & Gardan)	Bacteria	CPC and ISC	No		160	Survey for its potential presence in Kenya and conduct full PRA
Pectobacterium atrosepticum (van Hall) Gardan, Gouy, Christen & Samson	Bacteria	CPC and ISC	Yes	Tanzania	150	Survey for its potential presence in Kenya and conduct full PRA
Faba bean necrotic yellows virus	Virus	CPC and ISC	Yes	Ethiopia	150	Survey for its potential presence in Kenya
Ralstonia solanacearum Race 2 (Smith) Yabuuchi et al. emend. Safni et al	Bacteria	CPC and ISC	Yes	Ethiopia	140	Survey for its potential presence in Kenya
Banana bunchy top virus	Virus	CPC and ISC	No		140	Conduct a full PRA
Peronospora sparsa (Berkeley)	Chromista	CPC and ISC	No		120	Survey for its potential presence in Kenya and conduct full PRA
Helminthosporium solani (Durieu & Montagne)	Fungus	CPC and ISC	No		120	Survey for its potential presence in Kenya
Cucurbit yellow stunting disorder virus	Virus	CPC and ISC	No		120	Conduct a full PRA
Candidatus Liberibacter solanacearum (Liefting, Perez-Egusquiza & Clover)	Bacteria	CPC and ISC	No		105	Conduct a full PRA and surveillance
Candidatus Phytoplasma asteris (Lee, Gundersen-Rindal, Davis, Bottner, Marcone & Seemüller)	Bacteria	CPC and ISC	No		105	Conduct a full PRA
Synchytrium endobioticum (Schilbersky) Percival	Fungus	CPC and ISC	No		105	Conduct a full PRA
Tilletia controversa (Kühn)	Fungus	CPC and ISC	No		105	Conduct a full PRA
Urocystis agropyri (G. Preuss) J. Schröter	Fungus	CPC and ISC	No		105	Conduct a full PRA
Potato spindle tuber viroid	Viroid	CPC and ISC	Yes	Kenya and Tanzania	100	Survey for its potential presence in Kenya and conduct full PRA
Squash leaf curl virus	Virus	CPC and ISC	No		100	Conduct a full PRA

Table 3 (continued)

Species	Kingdom	Source	Present in neighbouring country?	Countries	Score	Suggested actions
Gibberella circinata (Nirenberg & O'Donnell)	Fungus	CPC and ISC	No		96	Conduct a full PRA
Fusarium oxysporum f.sp. *cubense* TR4 (E. F. Smith) Snyder & Hansen	Fungus	CPC and ISC	No		90	Conduct a full PRA
Pepino mosaic virus	Virus	CPC and ISC	No		90	Conduct a full PRA

were already reported in Africa but not in neighbouring countries except *A. arachidis* which is reported in the neighbouring Uganda (Talwana et al. 2008; Lesufi et al. 2015). All are most likely to arrive with their host plants as contaminants (seed-borne) although *A. arachidis* could arrive from across the border in Uganda in soil (stowaway). Since all the nine assessed species received risk scores of 54 (minimum) and above, suggestions for the next steps have been made which include conducting a full PRA and surveillance (Table 2). This exception was made because the assessed nematodes were very few and all met the minimum requirement (risk score of 54 and above) for action.

Pathogenic organisms

In total, 41 pathogenic organisms were assessed: 15 bacteria, three Chromista (water moulds), 16 fungi, one viroid and six viruses (Supplementary file S2). The scores ranged from 18 for *Phytoplasma pyri* to 175 for *Xanthomonas citri* and *Ceratocystis fimbriata* (Supplementary file S2). Four bacterial species (*D. solani*, *D. dadantii*, *P. parmientieri*, *C. sepedonicus*, *D. dianthicola*) and one viral species (potato mop-top virus (PMTV)) had not been recorded in Africa at the time of the assessment (Supplementary file S2), and all are known to affect *S. tuberosum* (Linnaeus) (Toth et al. 2011; Abbas and Madadi 2016; Baharuddin et al. 2019; de Neergaard et al. 2020). Of the 36 pathogenic species recorded to be present in Africa at the time of the assessment, 10 were present in all countries neighbouring Kenya except South Soudan (Supplementary file S2). They included *X. citri*, *C. fimbriata*, *P. atrosepticum*, Faba bean necrotic yellows virus, *Ralstonia solanacearum* Race 2, Potato spindle tuber viroid (PSTVd), *Claviceps fusiformis*, *Phytophthora colocasiae*, *Puccinia substriata* var. *substriata*, and *Xanthomonas fragariae*. They all scored more than the 54 minimum risk score with all also scoring more than the 3 minimum score for likelihood of entry and establishment indicating possible entry and establishment in Kenya (Table 3 and Supplementary file S2).

The majority (85%) of pathogens were likely to arrive as contaminants on commodities, especially as seed-borne pathogens, and/or as stowaways (68%) if the pathogen could be carried in soil (soil-borne) or by a vector (virus and viroid). One of the viruses assessed that could arrive either in seed (contaminant) or in soil (stowaway) was PMTV (Calvert and Harrison 1966; Jones and Harrison 1969; Latvala-Kilby et al. 2009). Unlike many viruses that are vectored by insects, PMTV is vectored by the fungus, *Spongospora subterranea* f.sp. *subterranea* (Jones and Harrison 1969; Kirk 2008), the causal agent of powdery scab in *S. tuberosum* (Harrison et al. 1997; Merz and Falloon 2009), and having a wide global distribution (Merz 2008). The first course of action suggested for the prioritised pathogenic species was to survey for potential presence in Kenya, particularly those that have been reported in neighbouring countries while for others especially those known to affect value chains prioritised by Kenya (MoALF 2019), full PRAs are proposed (Table 2). It is recommended that the rest of the species (not prioritised) are added to the plant health risk register to regularly assess change in risk.

Discussion

Horizon scanning, a method used in prioritization of IAS (Roy et al. 2014, 2017, 2019; Bayón and Vilà 2019) was applied in this study to identify plant pests that could be introduced in Kenya, become invasive and cause enormous socio-economic and biodiversity damage. The species were ranked according to their potential threat and appropriate actions suggested for some prioritised species. Since the exercise was conducted in 2018, four pest species have since been found to be present in Kenya. This demonstrates that for some of the assessed species and probably some that were eliminated because they were presumed absent in Africa and in Kenya, could have been present in Kenya at the time of assessment. This was caused by a gap in reporting which is mainly attributed to lack of or limited resources to update pest lists, organise horizon scanning to prioritise likely pest incursions, and conduct regular surveillances on prioritised pests (Kansiime et al. 2017). This results in most countries in SSA reacting to pest incursions rather than proactively stopping them. The four pest species include two arthropods (red gum lerp psyllid and the spotted wing drosophila) and two pathogenic organisms (the bacterial species, *P. parmentieri* and the viroid, potato spindle tuber viroid) (Kwadha et al. 2021).

The first arthropod, red gum lerp psyllid (*Glycaspis brimblecombei*) was found in Kenya in 2018 but reported in 2020 (Wondafrash et al. 2020) indicating it was already present at the time of the assessment. Its risk was scored as high judging by the likelihood scores for entry, establishment, and economic impact (Supplementary file S2). This is because it had recently invaded eucalyptus production areas in different parts of the world, including several African countries. In all these areas, it quickly became a pest of commercially important eucalyptus species, such as *Eucalyptus camaldulensis*. It remains to be seen how damaging the species becomes in Kenya, as in several regions, the intentional or accidental introduction of its specific parasitoid, *Psyllaephagus bliteus* entirely or partially controlled the pest (Caleca et al. 2018). If the economic impact in Kenya is significant, biological control should be considered. The second arthropod, *D. suzukii* is a fruit pest of Asian origin that had only been reported in Morocco and Réunion in Africa at the time the assessment despite its rapid worldwide spread in recent years hence the moderate overall risk score of around 60. It is mainly a pest of temperate climates that does not cope well with high temperatures (Ørsted and Ørsted 2019). Its preferred hosts include strawberry (*Fragaria ananassa*), blackberry (*Rubus fruticosus*), blueberry (*Vaccinium corymbosum*), and raspberry (*Rubus idaeus*) (Garcia 2020). These hosts are not yet major crops in Kenya hence the likelihood of establishment and potential economic consequences were both scored as moderate (3). Kwadha et al. (2021) identified *D. suzukii* on *R. idaeus*, *F. ananassa*, *V. corymbosum* and *Punica grantum* (pomegranates) at one farm in Nakuru county but not the other five counties were the sampling was also done. Although Kwadha et al. (2021) did not indicate the likely pathway, the pest could probably have been introduced through commodities. Berry (2020) indicated that *D. suzukii* lays its eggs and feeds internally as immatures within fruits making spread through fruits the most important pathway. The second but unlikely pathway could be soil where pupation occurs (Berry 2020). The main hosts which are also indicated above are becoming increasingly grown in the Kenyan highlands raising the likely potential economic impact (Kwadha et al. 2021). Therefore, possibilities for containment and/or management measures such as biological control should therefore be assessed (Kwadha et al. 2021; Seehausen et al. 2021).

One of the pathogenic organisms, the bacterial species *P. parmentieri* originally belonged to the soft rot *Enterobacteriaceae* (Ma et al. 2007) but has since been transferred to soft rot *Pectobacteriaceae* (Adeolu et al. 2016; van der Wolf et al. 2021). *Pectobacterium wasabiae*, a species originally transferred to *P. parmentieri* (Khayi et al. 2016) was confirmed in Kenya through surveys conducted in 2016/2017 (Kamau et al. 2019). *Pectobacterium parmentieri* was scored as having a relatively low likelihood of entry because it was only reported in South Africa at the time, a country with less trade in *S. tuberosum* with Kenya offering limited or no pathways (contaminants) however, a high likelihood of establishing was suggested resulting in significant economic damage because other *Pectobacterium* species have been reported in Kenya (Kamau et al. 2019). Similarly, PSTVd, the second pathogenic organism judged absent in Africa and Kenya at the time of assessment, has since been reported in Ghana and Kenya in *Solanaceous* uncultivated species (*S. anguivi*, *S. anomalum*, *S. cerasiferum*, *S. coagulans*, *S. dasyphyllum*, *S. incanum*, *S. macrocarpon* and *S. virginianum*) and in Kenya in tree tomato (*S. betaceum*) (Skelton et al. 2019; Kinoga et al. 2021). Although the viroid also naturally infects pepper and chili (*Capsicum annuum*), pepino (*S. muricatum*), eggplant (*S. melongena*), tomato (*Lycopersicon esculentum*), and *S. tuberosum* (Mackie et al. 2002; Verhoeven et al. 2004, 2010), no report of its presence in any of the aforementioned crops is available although this does not necessary confirm absence as lessons have demonstrated (Wondafrash et al. 2020; Kwadha et al. 2021).

Potato spindle tuber viroid is designated a quarantine pest in many countries therefore, detection surveys are suggested to confirm presence in key export crops especially chilli and flowers as well as food security crops especially *S. tuberosum*, which is widely grown by smallholder farmers in Kenya, yet this viroid is known to cause major loses in yield and reduce tuber quality (Owens 2007; Kochetov et al. 2021). The viroid is known to be transmitted through contact (Verhoeven et al. 2010) indicating it may be moved between plant species through crop handling which suggests probable presence in *C. annuum*, *S. muricatum*, *S. melongena*, *L. esculentum*, and *S. tuberosum* since *S. betaceum* is also widely grown in the similar areas in Kenya like the mentioned crops (Waswa et al. 2020; MoALF 2021; Kinoga et al. 2021). Although studies demonstrate the viroid can also be transmitted by the aphid species, *M. persicae*, this is only possible if the source plant is infected with both the viroid and potato leafroll virus (PLRV) (Syller et al. 1997; Syller 2001). The capsid protein of PLRV encapsulates the viroid resulting in transmission by *M. persicae*. However, PLRV and *M. persicae* are not known to infect any of the hosts in which PSTVd was reported in Kenya leaving transmission between species through crop handling the main possible mechanism; within species through true seed if it is present in the mentioned crops (Verhoeven et al. 2010) or by aphids if present in *S. tuberosum* (Syller et al. 1997; Syller 2001).

The above examples suggest there may be other species present that have not yet been detected. Thus, one of the follow-up actions (Tables 1, 2 and 3) for prioritised species, particularly those recorded as present in neighbouring countries, is detection surveys. Examples include *B. tabaci* (MED species) (Misaka et al. 2020), *A. gracilipes* (Löhr 1992), *Bruchus pisorum* (Mendesil et al. 2016), *Pseudaulacaspis pentagona* (CABI 2021b), *Trogoderma granarium* (EPPO 1981); the nematode *A. arachidis* (Talwana et al. 2008; Lesufi et al. 2015); and the pathogenic species such as *C. fimbriata* (Rouxa et al. 2001), *X. citri* (Balestra et al. 2008; Derso et al. 2009; Ference et al. 2018), *P. atrosepticum* (CABI 2021b), and Faba bean necrotic yellows virus (Abraham et al. 2000). Other species were adjudged as having a moderate likelihood of entry but had a high overall score due to the high scores obtained for likelihood of establishment and magnitude of socio-economic impact. Kenya has prioritized a number of value chains under the Agricultural Sector Transformation and Growth Strategy, 2019–2029 as key to improving livelihoods and supporting economic growth (MoALF 2019). Therefore, species which could affect the prioritised value chains are appropriate targets for conducting a full PRA. The outcome of the PRA will advise implementation of import controls and the preparation of contingency plans. Species in this category included *Thrips palmi* (melon thrips), *Cacoecimorpha pronubana*, *Euwallacea perbrevis* (tea shot-hole borer), and *Peronospora sparsa* (cause of downy mildew of roses) among others.

A further group of species scored low on likelihood of entry, but high on likelihood of establishment and socioeconomic impact, so they were not near the top of the overall ranking. Several of the species in this group are potential pests of *S. tuberosum*, including *D. solani*, *D. dadantii*, *D. dianthicola, C. sepedonicus*, *Phoma exigua* f.sp. *foveata*, and *Synchytrium endobioticum*). *Solanum tuberosum* is an important crop in Kenya which has recently suffered from new pests such as PCN (Mwangi et al. 2015; Mburu et al. 2018, 2020). For several of these species, adjusting the score for likelihood of entry upwards by 1 would have put the final overall score in the top 20 prioritised pests. This suggests that follow-up activity should not necessarily be limited to the highest-ranking or prioritised species. Secondly, the scores need to be regularly reviewed, thus implementing a plant health risk register such as the one implemented by the United Kingdom (Baker et al. 2014) to which all assessed species and also those identified through interceptions at border points should be considered.

The methodology for horizon scanning described here is an adaption of previously used methods (Sutherland et al. 2011; Roy et al. 2014, 2019), adjusted for the Kenyan context. Such pest prioritisation schemes have emerged particularly in the last decade to support plant health decision making by risk managers and policy makers in prioritising the large number of potential invasive species (MacLeod and Lloyd 2020). Most of these prioritisation or risk ranking systems have been deployed in high income countries, so the use of this approach in Kenya was novel. The approach adopted worked well, bringing together SMEs from a range of organisations. They achieved consensus on modifying the criteria for the scores, as well as in the final scoring when there were discrepancies between the experts' scores. As invasive plants were excluded from the exercise, further work would be required to adjust the definitions to cater for invasive plants. The area in which the SMEs felt least comfortable was in scoring of potential impact on biodiversity. Few species scored highly on impact on biodiversity; three arthropods and two pathogens had a risk score of 4. This may be because socioeconomic impacts of invasive arthropods and pathogens are generally better known than their impact on biodiversity, and confidence in the impact on biodiversity score was often low. Invasive ants are an exception because they are considered to have serious effects on biodiversity worldwide (Mikissa et al. 2013; Mothapo and Wossler 2017; Mbenoun Masse et al. 2017). Two ants in our assessment had a high score for their potential impact on biodiversity, *A. gracilipes* and *Linepithema humile*. Many non-native herbivores and plant pathogens are a serious global threat to native biodiversity and ecosystems and in some areas, they are already a threat (Kenis et al. 2009; Ghelardini et al. 2017).

It was noted that a change of 1 point in a score could move a pest many places up the list of priorities, and pest prioritisation schemes are not without shortcomings (MacLeod and Lloyd 2020). Rather than being a one-off activity, the results should be reviewed regularly, particularly in the light of any new information that might arise. Thus, part of the outcome of a horizon scanning process such as this could be systematic monitoring of information sources to detect possible changes to risk, which can be recorded in a plant health risk register. Kenya does not have a plant health risk register or list of prioritised pests for prevention, and thus the horizon scanning process adopted here could provide the basis for such a register. Given the practicality of the approach and the widespread lack of pest prioritisation in SSA, we propose that the approach reported here could benefit many other countries on the continent if adopted. It could also be implemented at a sub-regional level, such as the East African Community (Eastern Africa), Southern African Development Community (Southern Africa) or Economic Community of West African States (Western Africa), and possibly by the African Union, for which a new Plant Health strategy is currently under development. Sub-regional- or regional-based assessments are indeed more important than country-based assessments because lessons have demonstrated that once an invasive pest lands on the African continent or sub-region, control of spread across countries is virtually impossible due to weak or non-existent border biosecurity and porous borders.

Authors' contributions All authors participated in the assessments of likely IAS. Joseph Mulema, Roger Day and Marc Kenis put together the initial drafts of the manuscript while all other authors read, contributed further edits and approved the final manuscript.

Funding This work was financially supported by the Foreign, Commonwealth and Development Office (FCDO), UK, the Directorate-General for International Cooperation (DGIS), Netherlands, the European Commission Directorate-General for International Cooperation and Development (DEVCO) and the Swiss Agency for Development and Cooperation (SDC) through CABI's Action on Invasives and PlantwisePlus Programmes. CABI is an international intergovernmental organisation, and we gratefully acknowledge the core financial support from our member countries and lead agencies. See https://www.cabi.org/aboutcabi/who-we-work-with/key-donors for details.

Availability of data and material All additional relevant data and materials have been submitted as supplementary materials.

Code availability Not applicable.

Declarations

Conflicts of interest None.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

References

Abbas A, Madadi M (2016) A review paper on potato mop-top virus (PMTV): occurrence, properties and management. World J Biotechnol 1:127–132. https://doi.org/10.33865/wjb.001.03.0012

Abraham A, Makkouk KM, Gorfu D et al (2000) Survey of faba bean (*Vicia faba* L.) virus diseases in Ethiopia. Phytopathol Mediterr 39:277–282

Adams IP, Miano DW, Kinyua ZM et al (2013) Use of next-generation sequencing for the identification and characterization of Maize chlorotic mottle virus and Sugarcane mosaic virus causing maize lethal necrosis in Kenya. Plant Pathol 62:741–749. https://doi.org/10.1111/j.1365-3059.2012.02690.x

Adams IP, Harju VA, Hodges T et al (2014) First report of maize lethal necrosis disease in Rwanda. New Dis Rep 29:22–22. https://doi.org/10.5197/j.2044-0588.2014.029.022

Adeolu M, Alnajar S, Naushad S, Gupta RS (2016) Genome-based phylogeny and taxonomy of the "*Enterobacteriales*": proposal for *Enterobacterales* ord. nov. divided into the families Enterobacteriaceae, *Erwiniaceae* fam. nov., *Pectobacteriaceae* fam. nov., *Yersiniaceae* fam. nov., *Hafniaceae* fam. nov., *Morganellaceae* fam. nov., and *Budviciaceae* fam. nov. Int J Syst Evol Microbiol 66:5575–5599. https://doi.org/10.1099/ijsem.0.001485

Andae G (2012) Farmers panic over spread of maize disease. https://nation.africa/kenya/Counties/Farmers+panic+over+spread+of+maize+disease+/1107872-1415526-l96cmi/index.html. Accessed 26 Jan 2022

Baharuddin, Pabborong A, Kuswinanti T et al (2019) Occurance of *Clavibacter michiganensis* subsp. *sepedonicus* on potato in South Sulawesi. In: IOP Conference Series: Earth and Environmental Science, vol 355, p 012081. https://doi.org/10.1088/1755-1315/355/1/012081

Baker RHA, Anderson H, Bishop S et al (2014) The UK Plant Health Risk Register: a tool for prioritizing actions. EPPO Bull 44:187–194. https://doi.org/10.1111/epp.12130

Balestra GM, Sechler A, Schuenzel E, Schaad NW (2008) First report of citrus canker caused by *Xanthomonas citri* in Somalia. Plant Dis 92:981–981. https://doi.org/10.1094/pdis-92-6-0981C

Bayón Á, Vilà M (2019) Horizon scanning to identify invasion risk of ornamental plants marketed in Spain. NeoBiota 52:47–86. https://doi.org/10.3897/neobiota.52.38113

Berry JA (2020) *Drosophila suzukii*: pathways and pathway management by regulation. In: Garcia FRM (ed) *Drosophila suzukii* management. Springer International Publishing, Cham, pp 29–39

Blackburn TM, Essl F, Evans T et al (2014) A unified classification of alien species based on the magnitude of their environmental impacts. PLOS Biol 12:e1001850. https://doi.org/10.1371/journal.pbio.1001850

Braidwood L, Quito-Avila DF, Cabanas D et al (2018) Maize chlorotic mottle virus exhibits low divergence between differentiated regional sub-populations. Sci Rep 8:1173–1173. https://doi.org/10.1038/s41598-018-19607-4

CABI (2021a) Crop protection compendium. www.cabi.org/cpc

CABI (2021b) Invasive species compendium. www.cabi.org/isc

Caffrey JM, Baars JR, Barbour JH et al (2014) Tackling invasive alien species in Europe: the top 20 issues. Manag Biol Invasions 5:1–20. https://doi.org/10.3391/mbi.2014.5.1.01

Caleca V, Bella S, La Pergola A et al (2018) Environmental factors impact and incidence of parasitism of *Psyllaephagus bliteus* Riek (Hymenoptera: *Encyrtidae*) on populations of *Glycaspis brimblecombei* Moore (Hemiptera: *Aphalaridae*) in Mediterranean climatic areas. J Zool 101:89–100. https://doi.org/10.19263/REDIA-101.18.12

Calvert EL, Harrison BD (1966) Potato mop-top, a soilborne virus. Plant Pathol 15:134–139. https://doi.org/10.1111/j.1365-3059.1966.tb00333.x

De Groote H, Kimenju SC, Munyua B et al (2020) Spread and impact of fall armyworm (*Spodoptera frugiperda* J.E. Smith) in maize production areas of Kenya. Agric Ecosyst Environ 292:106804. https://doi.org/10.1016/j.agee.2019.106804

de Neergaard E, Harding S, Czajkowski R et al (2020) *Pectobacterium atrosepticum* (van Hall) Gardan et al. as a causal agent of potato blackleg in Greenland. Eur J Plant Pathol 157:425–431. https://doi.org/10.1007/s10658-020-01994-y

Derso E, Vernière C, Pruvost O (2009) First Report of *Xanthomonas citri* pv. *citri*-A* causing citrus canker on lime in Ethiopia. Plant Dis 93:203–203. https://doi.org/10.1094/pdis-93-2-0203B

Desneux N, Luna MG, Guillemaud T, Urbaneja A (2011) The invasive South American tomato pinworm, Tuta absoluta, continues to spread in Afro-Eurasia and beyond: the new threat to tomato world production. J Pest Sci 84:403–408. https://doi.org/10.1007/s10340-011-0398-6

EPPO (1981) Data sheets on quarantine organisms No. 121, *Trogoderma granarium*. OEPP/EPPO

Eschen R, Beale T, Bonnin JM et al (2021) Towards estimating the economic cost of invasive alien species to African crop and livestock production. CABI Agric Biosci 2:18. https://doi.org/10.1186/s43170-021-00038-7

Essl F, Bacher S, Blackburn TM et al (2015) Crossing frontiers in tackling pathways of biological invasions. Bioscience 65:769–782. https://doi.org/10.1093/biosci/biv082

Essl F, Dullinger S, Genovesi P et al (2019) A conceptual framework for range-expanding species that track human-induced environmental change. Bioscience 69:908–919. https://doi.org/10.1093/biosci/biz101

Faulkner KT, Hurley BP, Robertson MP et al (2017) The balance of trade in alien species between South Africa and the rest of Africa. Bothalia - Afr Biodivers Conserv 47:1–16

Faulkner KT, Robertson MP, Wilson JRU (2020) Stronger regional biosecurity is essential to prevent hundreds of harmful biological invasions. Glob Change Biol 26:2449–2462. https://doi.org/10.1111/gcb.15006

Ference CM, Gochez AM, Behlau F et al (2018) Recent advances in the understanding of *Xanthomonas citri* ssp. *citri* pathogenesis and citrus canker disease management. Mol Plant Pathol 19:1302–1318. https://doi.org/10.1111/mpp.12638

Gallardo B, Zieritz A, Adriaens T et al (2016) Trans-national horizon scanning for invasive non-native species: a case study in western Europe. Biol Invasions 18:17–30. https://doi.org/10.1007/s10530-015-0986-0

Garcia FRM (2020) Introduction to *Drosophila suzukii* management. In: Garcia FRM (ed) *Drosophila suzukii* Management. Springer, Cham, pp 1–9

Gassó N, Sol D, Pino J et al (2009) Exploring species attributes and site characteristics to assess plant invasions in Spain. Divers Distrib 15:50–58. https://doi.org/10.1111/j.1472-4642.2008.00501.x

Ghelardini L, Luchi N, Pecori F et al (2017) Ecology of invasive forest pathogens. Biol Invasions 19:3183–3200. https://doi.org/10.1007/s10530-017-1487-0

Guimapi RYA, Mohamed SA, Okeyo GO et al (2016) Modeling the risk of invasion and spread of *Tuta absoluta* in Africa. Ecol Complex 28:77–93. https://doi.org/10.1016/j.ecocom.2016.08.001

Harrison JG, Searle RJ, Williams NA (1997) Powdery scab disease of potato—a review. Plant Pathol 46:1–25. https://doi.org/10.1046/j.1365-3059.1997.d01-214.x

Hulme PE, Bacher S, Kenis M et al (2008) Grasping at the routes of biological invasions: a framework for integrating pathways into policy. J Appl Ecol 45:403–414. https://doi.org/10.1111/j.1365-2664.2007.01442.x

IPPC Secretariat (2021) International Standards for Phytosanitary Measures (ISPM), Publication No. 5: Glossary of Phytosanitary Terms. Food and Agriculture Organization of the United Nations, Secretariat of the International Plant Protection Convention (IPPC), Rome

Jones RAC, Harrison BD (1969) The behaviour of potato mop-top virus in soil, and evidence for its transmission by *Spongospora subterranea* (Wallr.) Lagerh. Ann Appl Biol 63:1–17. https://doi.org/10.1111/j.1744-7348.1969.tb05461.x

Kagoda F, Gidoi R, Isabirye BE (2016) Status of maize lethal necrosis in eastern Uganda. Afr J Agric Res 11:652–660. https://doi.org/10.5897/ajar2015.10616

Kamau JW, Ngaira J, Kinyua J et al (2019) Occurence of pectinolytic bacteria causing blackleg and soft rot of potato in Kenya. J Plant Pathol 101:689–694. https://doi.org/10.1007/s42161-018-00219-w

Kansiime M, Mulema J, Karanja D et al (2017) Crop pests and disease management in Uganda: status and investment needs. Platform for Agricultural Risk Management (PARM), International Fund for Agricultural Development (IFAD), Rome

Kenis M, Auger-Rozenberg M-A, Roques A et al (2009) Ecological effects of invasive alien insects. Biol Invasions 11:21–45. https://doi.org/10.1007/s10530-008-9318-y

Khayi S, Cigna J, Chong TM et al (2016) Transfer of the potato plant isolates of *Pectobacterium wasabiae* to *Pectobacterium parmentieri* sp. nov. Int J Syst Evol Microbiol 66:5379–5383

Kinoga MN, Kuria PK, Miano DW, Wasilwa LA (2021) First report of potato spindle tuber viroid infecting tree tomato in Kenya in mixed infection with Potato virus Y. New Dis Rep 44:e12029. https://doi.org/10.1002/ndr2.12029

Kirk HG (2008) Mop-top virus, relationship to its vector. Am J Potato Res 85:261–265. https://doi.org/10.1007/s12230-008-9021-7

Kiruwa FH, Mutiga S, Njuguna J et al (2020) Status and epidemiology of maize lethal necrotic disease in Northern Tanzania. Pathogens 9:4. https://doi.org/10.3390/pathogens9010004

Kochetov AV, Pronozin AY, Shatskaya NV et al (2021) Potato spindle tuber viroid. Vavilovskii Zhurnal Genet Sel 25:269–275. https://doi.org/10.18699/VJ21.030

Kwadha CA, Okwaro LA, Kleman I et al (2021) Detection of the spotted wing drosophila, *Drosophila suzukii*, in continental sub-Saharan Africa. J Pest Sci 94:251–259. https://doi.org/10.1007/s10340-021-01330-1

Latvala-Kilby S, Aura JM, Pupola N et al (2009) Detection of potato mop-top virus in potato tubers and sprouts: combinations of RNA2 and RNA3 variants and incidence of symptomless infections. Phytopathology 99:519–531. https://doi.org/10.1094/phyto-99-5-0519

Lesufi MM, Swart A, Mc Donald AH et al (2015) Morphological and molecular studies on *Aphelenchoides arachidis* Bos, 1977 (Tylenchina: Aphelenchoididae) from groundnuts in South Africa. Nematology 17:433–445. https://doi.org/10.1163/15685411-00002879

Löhr B (1992) The pugnacious ant, *Anoplolepis custodiens* (Hymenoptera: *Formicidae*), and its beneficial effect on coconut production in Tanzania. Bull Entomol Res 82:213–218. https://doi.org/10.1017/S0007485300051750

Louie R (1980) Sugarcane mosaic virus in Kenya. Plant Dis 64:944–947

Lukanda M, Owati A, Ogunsanya P et al (2014) First Report of Maize chlorotic mottle virus Infecting Maize in the Democratic Republic of the Congo. Plant Dis 98:1448–1448. https://doi.org/10.1094/pdis-05-14-0484-pdn

Ma B, Hibbing ME, Kim H-S et al (2007) Host range and molecular phylogenies of the soft rot enterobacterial genera *Pectobacterium* and *Dickeya*. Phytopathology 97:1150–1163. https://doi.org/10.1094/phyto-97-9-1150

Macharia I, Kimani E, Koome F et al (2017) First report and distribution of the papaya mealybug, *Paracoccus marginatus*, in Kenya. J Agric Urban Entomol 33:142–150. https://doi.org/10.3954/jaue17-02.1

Mackie AE, McKirdy SJ, Rodoni B, Kumar S (2002) Potato spindle tuber viroid eradicated in Western Australia. Australas Plant Pathol 31:311–312. https://doi.org/10.1071/AP02033

MacLeod A, Lloyd S (2020) The emergence of prioritisation systems to inform plant health biosecurity policy decisions. Emerg Top Life Sci 4:463–471. https://doi.org/10.1042/ETLS20200341

Mahuku G, Lockhart BE, Wanjala B et al (2015) Maize lethal necrosis (MLN), an emerging threat to maize-based food security in sub-Saharan Africa. Phytopathology 105:956–965. https://doi.org/10.1094/phyto-12-14-0367-fi

Makiche E (2012) Despair as mysterious bug destroys maize farms. In: The Standard. https://www.standardmedia.co.ke/the-standard/article/2000049775/despair-as-mysterious-bug-destroys-maize-farms. Accessed 26 Jan 2022

Maundu P, Kibet S, Morimoto Y et al (2009) Impact of *Prosopis juliflora* on Kenya's semi-arid and arid ecosystems and local livelihoods. Biodiversity 10:33–50. https://doi.org/10.1080/14888386.2009.9712842

Mbenoun Masse PS, Tindo M, Kenne M et al (2017) Impact of the invasive ant *Wasmannia auropunctata* (Formicidae: *Myrmicinae*) on local ant diversity in southern Cameroon. Afr J Ecol 55:423–432. https://doi.org/10.1111/aje.12366

Mburu H, Cortada L, Mwangi G et al (2018) First report of potato cyst nematode *Globodera pallida* infecting potato (*Solanum tuberosum*) in Kenya. Plant Dis 102:1671. https://doi.org/10.1094/PDIS-11-17-1777-PDN

Mburu H, Cortada L, Haukeland S et al (2020) Potato cyst nematodes: a new threat to potato production in East Africa. Front Plant Sci 11:1–13. https://doi.org/10.3389/fpls.2020.00670

Mendesil E, Shumeta Z, Anderson P, Rämert B (2016) Smallholder farmers' knowledge, perceptions and management of pea weevil in north and north-western Ethiopia. Crop Prot 81:30–37. https://doi.org/10.1016/j.cropro.2015.12.001

Mengesha GG, Kedir Mohammed B, Sultan Salo K (2019) Management of maize lethal necrosis disease through hand weeding and insecticide applications at Arba Minch in Southern Ethiopia. Cogent Food Agric 5:1705746. https://doi.org/10.1080/23311932.2019.1705746

Merz U (2008) Powdery scab of potato—occurrence, life cycle and epidemiology. Am J Potato Res 85:241. https://doi.org/10.1007/s12230-008-9019-1

Merz U, Falloon RE (2009) Review: powdery scab of potato—increased knowledge of pathogen biology and disease epidemiology for effective disease management. Potato Res 52:17–37. https://doi.org/10.1007/s11540-008-9105-2

Mikissa JB, Jeffery K, Fresneau D, Mercier JL (2013) Impact of an invasive alien ant, *Wasmannia auropunctata* Roger., on a specialised plant–ant mutualism, *Barteria fistulosa* Mast. and *Tetraponera aethiops* F. Smith., in a Gabon forest. Ecol Entomol 38:580–584. https://doi.org/10.1111/een.12057

Misaka BC, Wosula EN, Marchelo-d'Ragga PW et al (2020) Genetic diversity of *Bemisia tabaci* (Gennadius) (Hemiptera: *Aleyrodidae*) colonizing sweet potato and cassava in South Sudan. Insects 11:58. https://doi.org/10.3390/insects11010058

MoALF (2019) Agricultural Sector Transformation and Growth Strategy, 2019–2029. Ministry of Agriculture, Livestock and Fisheries (MoALF), Nairobi

MoALF (2021) The National Potato Council Strategy 2021–2025. Ministry of Agriculture, Livestock and Fisheries (MoALF), Nairobi

Mothapo NP, Wossler TC (2017) Patterns of floral resource use by two dominant ant species in a biodiversity hotspot. Biol Invasions 19:955–969. https://doi.org/10.1007/s10530-016-1336-6

Murono DA, Wabuyele E, Muoria PK, Abuto JO (2018) Distribution of *Parthenium hysterophorus* Linn and its Impacts on Biodiversity in Nyando Sub-County, Kisumu County, Kenya. Eur Acad Res 6:1599–1621

Mwangi JM, Kariuki GM, Waceke JW, Grundler FM (2015) First report of *Globodera rostochiensis* infesting potatoes in Kenya. New Dis Rep 31:18. https://doi.org/10.5197/j.2044-0588.2015.031.018

Nagoshi RN, Goergen G, Tounou KA et al (2018) Analysis of strain distribution, migratory potential, and invasion history of fall armyworm populations in northern Sub-Saharan Africa. Sci Rep 8:3710–3710. https://doi.org/10.1038/s41598-018-21954-1

OEPP/EPPO (2012) Decision-support scheme for an express pest risk analysis. EPPO Bull 42:457–462. https://doi.org/10.1111/epp.2591

Ørsted IV, Ørsted M (2019) Species distribution models of the Spotted Wing Drosophila (*Drosophila suzukii*, Diptera: Drosophilidae) in its native and invasive range reveal an ecological niche shift. J Appl Ecol 56:423–435. https://doi.org/10.1111/1365-2664.13285

Owens RA (2007) Potato spindle tuber viroid: the simplicity paradox resolved? Mol Plant Pathol 8:549–560. https://doi.org/10.1111/j.1364-3703.2007.00418.x

Peyton J, Martinou AF, Pescott OL et al (2019) Horizon scanning for invasive alien species with the potential to threaten biodiversity and human health on a Mediterranean island. Biol Invasions 21:2107–2125. https://doi.org/10.1007/s10530-019-01961-7

Rouxa J, Coutinhoa TA, Byabashaija MD, Wingfielda MJ (2001) Diseases of plantation Eucalyptus in Uganda. S Afr J Sci 97:16–18

Roy HE, Peyton J, Aldridge DC et al (2014) Horizon scanning for invasive alien species with the potential to threaten biodiversity in Great Britain. Glob Change Biol 20:3859–3871. https://doi.org/10.1111/gcb.12603

Roy HE, Hesketh H, Purse BV et al (2017) Alien pathogens on the horizon: opportunities for predicting their threat to wildlife. Conserv Lett 10:477–484. https://doi.org/10.1111/conl.12297

Roy HE, Bacher S, Essl F et al (2019) Developing a list of invasive alien species likely to threaten biodiversity and ecosystems in the European Union. Glob Change Biol 25:1032–1048. https://doi.org/10.1111/gcb.14527

Rwomushana I, Pratt C, González-Moreno P et al (2019) Tomato leaf miner (*Tuta absoluta*): impacts and coping strategies for Africa

Seehausen ML, Afonso C, Jactel H, Kenis M (2021) Classical biological control against insect pests in Europe, North

Africa, and the Middle East: what influences its success? NeoBiota 65:169–191. https://doi.org/10.3897/neobiota.65.66276
Simberloff D, Martin J-L, Genovesi P et al (2013) Impacts of biological invasions: what's what and the way forward. Trends Ecol Evol 28:58–66. https://doi.org/10.1016/j.tree.2012.07.013
Skelton A, Buxton-Kirk A, Fowkes A et al (2019) Potato spindle tuber viroid detected in seed of uncultivated *Solanum anguivi*, *S. coagulans* and *S. dasyphyllum* collected from Ghana, Kenya and Uganda. New Dis Rep 39:23. https://doi.org/10.5197/j.2044-0588.2019.039.023
Stewart LR, Willie K, Wijeratne S et al (2017) Johnsongrass mosaic virus contributes to maize lethal necrosis in East Africa. Plant Dis 101:1455–1462. https://doi.org/10.1094/pdis-01-17-0136-re
Sutherland WJ, Bailey MJ, Bainbridge IP et al (2008) Future novel threats and opportunities facing UK biodiversity identified by horizon scanning. J Appl Ecol 45:821–833. https://doi.org/10.1111/j.1365-2664.2008.01474.x
Sutherland WJ, Albon SD, Allison H et al (2010a) Review: the identification of priority policy options for UK nature conservation. J Appl Ecol 47:955–965. https://doi.org/10.1111/j.1365-2664.2010.01863.x
Sutherland WJ, Clout M, Côté IM et al (2010b) A horizon scan of global conservation issues for 2010. Trends Ecol Evol 25:1–7. https://doi.org/10.1016/j.tree.2009.10.003
Sutherland WJ, Fleishman E, Mascia MB et al (2011) Methods for collaboratively identifying research priorities and emerging issues in science and policy. Methods Ecol Evol 2:238–247. https://doi.org/10.1111/j.2041-210X.2010.00083.x
Syller M (2001) Potato leafroll virus-assisted aphid transmission of potato spindle tuber viroid to potato leafroll virus-resistant potato. J Phytopathol 149:195–201. https://doi.org/10.1046/j.1439-0434.2001.00600.x
Syller J, Marczewski W, Pawłowicz J (1997) Transmission by aphids of potato spindle tuber viroid encapsidated by potato leafroll luteovirus particles. Eur J Plant Pathol 103:285–289. https://doi.org/10.1023/A:1008648822190
Talwana HL, Butseya MM, Tusiime G (2008) Occurrence of plant parasitic nematodes and factors that enhance population build-up in cereal-based cropping systems in Uganda. Afr Crop Sci J 16:119–131
Toth IK, van der Wolf JM, Saddler G et al (2011) *Dickeya* species: an emerging problem for potato production in Europe. Plant Pathol 60:385–399. https://doi.org/10.1111/j.1365-3059.2011.02427.x
van der Wolf JM, Acuña I, de Boer SH et al (2021) Diseases caused by *Pectobacterium* and *Dickeya* species around the world. In: van Gijsegem F, van der Wolf JM, Toth IK (eds) Plant diseases caused by *Dickeya* and *Pectobacterium* species. Springer, Berlin, pp 215–261
Verhoeven J, Jansen CCC, Willemen TM et al (2004) Natural infections of tomato by Citrus exocortis viroid, Columnea latent viroid, potato spindle tuber viroid and tomato chlorotic dwarf viroid. Eur J Plant Pathol 110:823–831. https://doi.org/10.1007/s10658-004-2493-5
Verhoeven JThJ, Hüner L, Marn MV et al (2010) Mechanical transmission of Potato spindle tuber viroid between plants of *Brugmansia suaveoles*, *Solanum jasminoides* and potatoes and tomatoes. Eur J Plant Pathol 128:417–421. https://doi.org/10.1007/s10658-010-9675-0
Wangai AW, Redinbaugh MG, Kinyua ZM et al (2012) First report of maize chlorotic mottle virus and maize lethal necrosis in Kenya. Plant Dis 96:1582–1582. https://doi.org/10.1094/pdis-06-12-0576-pdn
Waswa SJ, Waceke JW, Nchore SB (2020) Diversity of plant parasitic nematodes of tree tomato (*Solanum betaceum* Cav.) in Kiambu and Embu Counties, Kenya. Middle East J Agric Res 9:605–616. https://doi.org/10.36632/mejar/2020.9.3.47
Weber E, Gut D (2004) Assessing the risk of potentially invasive plant species in central Europe. J Nat Conserv 12:171–179. https://doi.org/10.1016/j.jnc.2004.04.002
Westphal MI, Browne M, MacKinnon K, Noble I (2008) The link between international trade and the global distribution of invasive alien species. Biol Invasions 10:391–398. https://doi.org/10.1007/s10530-007-9138-5
Wondafrash M, Slippers B, Nambazimana A et al (2020) Distribution and genetic diversity of five invasive pests of Eucalyptus in sub-Saharan Africa. Biol Invasions 22:2205–2221. https://doi.org/10.1007/s10530-020-02250-4
Xie L, Zhang J, Wang Q et al (2011) Characterization of maize chlorotic mottle virus associated with maize lethal necrosis disease in China. J Phytopathol 159:191–193. https://doi.org/10.1111/j.1439-0434.2010.01745.x